Cost and Schedule Uncertainty

Analysis of Growth in Support of JCL

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Abstract

NASA formal probabilistic estimating guidance was first mentioned in February 2006 and later codified in 2009 Joint Cost and Schedule Confidence Level (JCL) policy. NASA has been continually making strides to hone the associated best practices and understanding for JCL analysis. One of the issues identified within the JCL construct is the lack of data-driven uncertainty guidance.

Typically uncertainty is modeled using a three point estimate at an activity or summary level. The low value represents the low extreme of uncertainty, the middle value represents the "most likely" value of the cost or duration, and the high value represents the high extreme of uncertainty.   In general, there is not a consistent set of practices or guidelines for how to determine the boundaries or distributions of the "natural" variation of cost and schedules in project development.   This has primarily been due to a lack of data, however over the past 7 years through the CADRe initiative NASA has been building a robust archive of project cost, schedule, and technical data at various points in a projects technical maturity. This data provided an opportunity to assess and determine if cost and schedule growth metrics could be developed for use in JCL analysis.

This presentation will provide insight into the analysis process and discuss the data challenges that existed within the study. Initial results of cost and schedule distributions will be provided as well as insight into the impact of complexity and technical maturity. This study provides direct benefits to analysts in developing or reviewing JCL models.

The JCL Modeling Challenge...
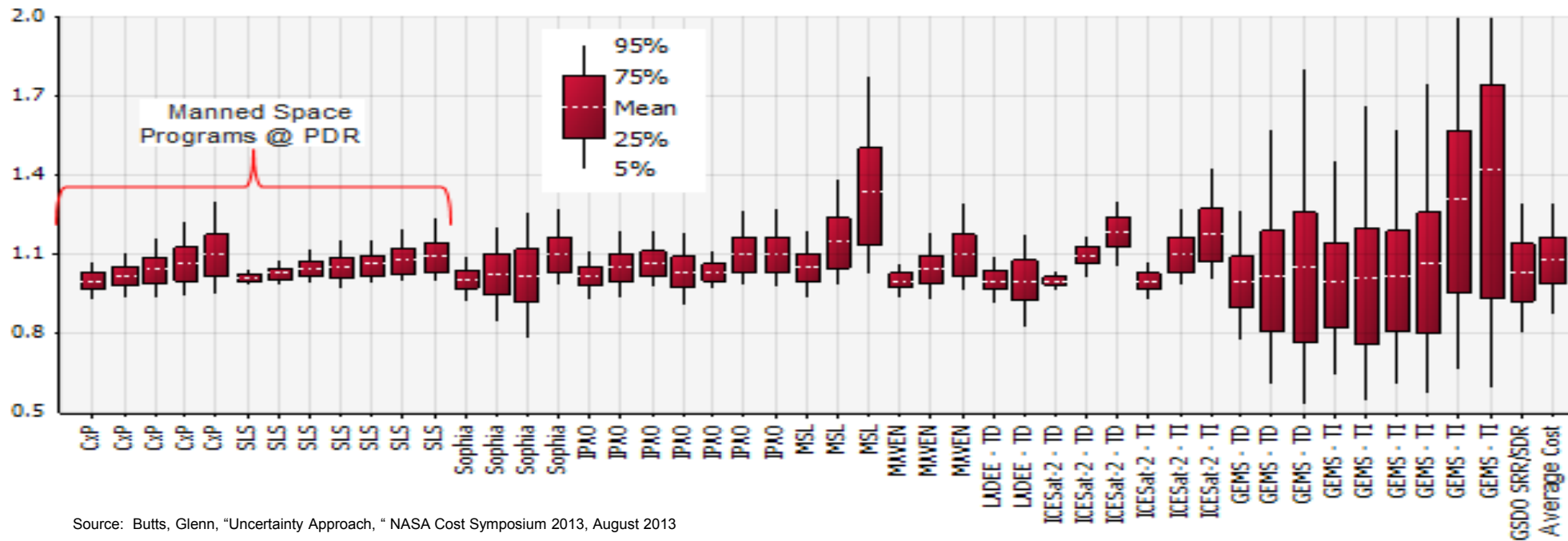

How do I separate risk from uncertainty?
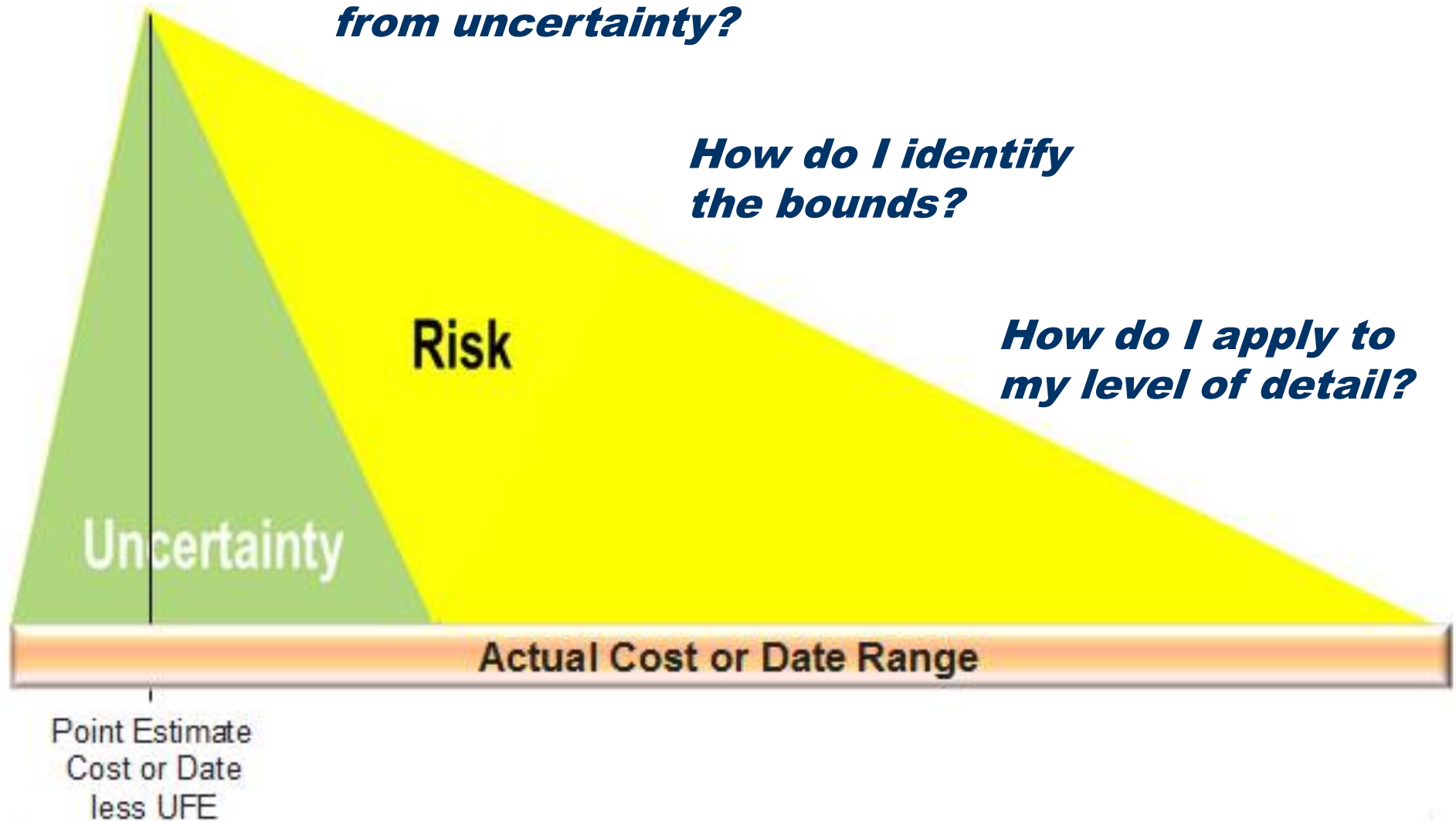
How do I identify the bounds?

How do I apply to my level of detail?

The Wild Wild West?

Source: Butts, Glenn, "Uncertainty Approach, " NASA Cost Symposium 2013, August 2013

In general, NASA projects have little consistency in setting the boundaries or distributions of the "natural" variation of cost and schedules

Furthermore, projects have difficulty distinguishing epistemic (discrete risks) in their risk registers from those that are included in natural uncertainty

Our community needs specific data, methodologies, and guidelines to help them determine appropriate levels of task duration and cost variation

In Pursuit of Perfection

Goal of the NASA OoE/CAD directed study was to determine a set of distributions based on historical data for duration and cost that could be applied to all levels of a project JCL model and account for risk
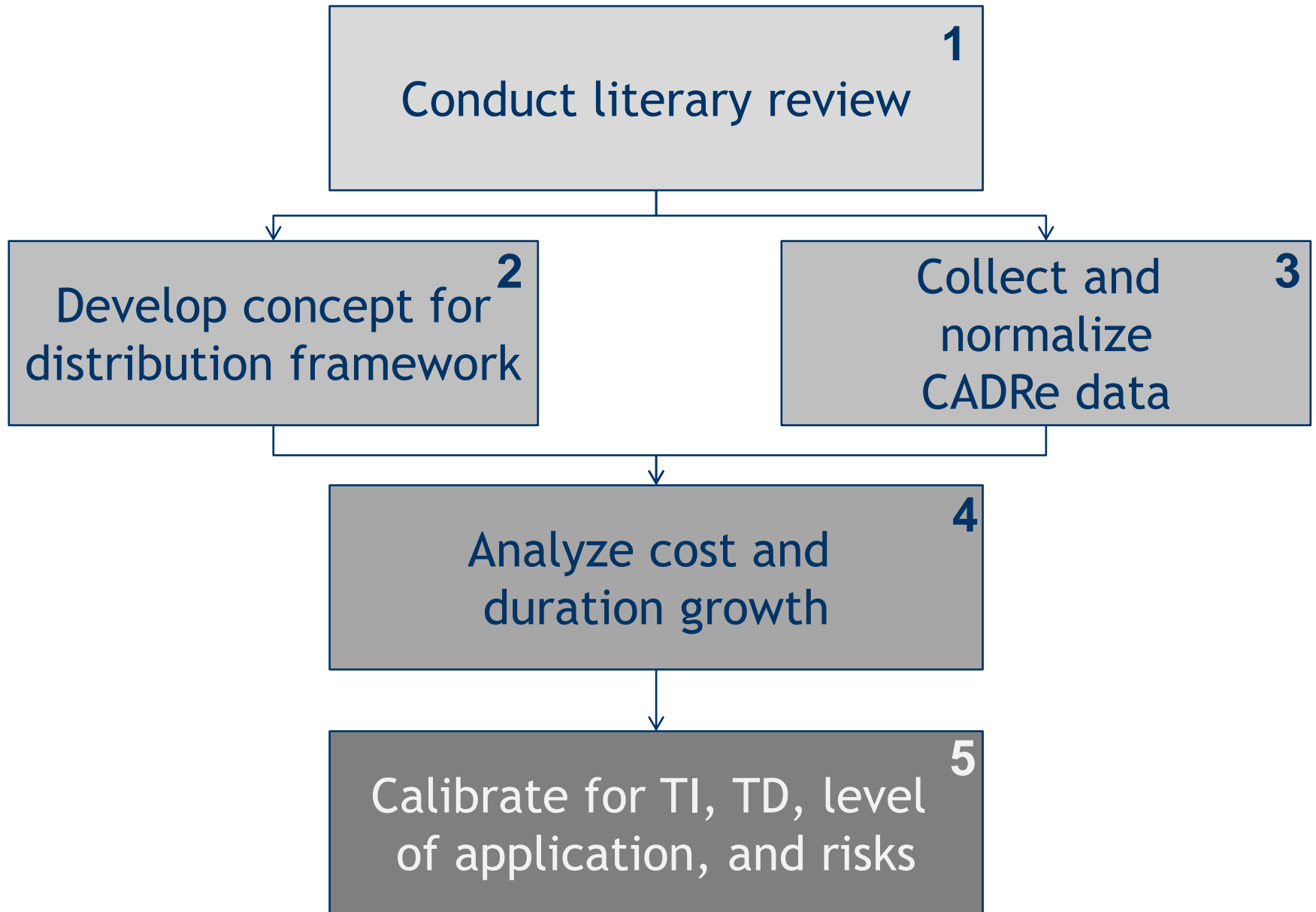
A Humbling Experience

Key Thoughts at the Beginning of our Journey

✓ Don't recreate the wheel

✓ Create DATA DRIVEN guidelines

✓ Establish framework that is easily understood and can evolve

✓ Account for topology/level/behavior

✓ Address risk/uncertainty "double accounting"

Our Path...

Conduct literary review `1`

Develop concept for distribution framework `2`

Collect and normalize CADRe data `3`

Analyze cost and duration growth `4`

Calibrate for TI, TD, level of application, and risks `5`

TECOLOTE RESEARCH

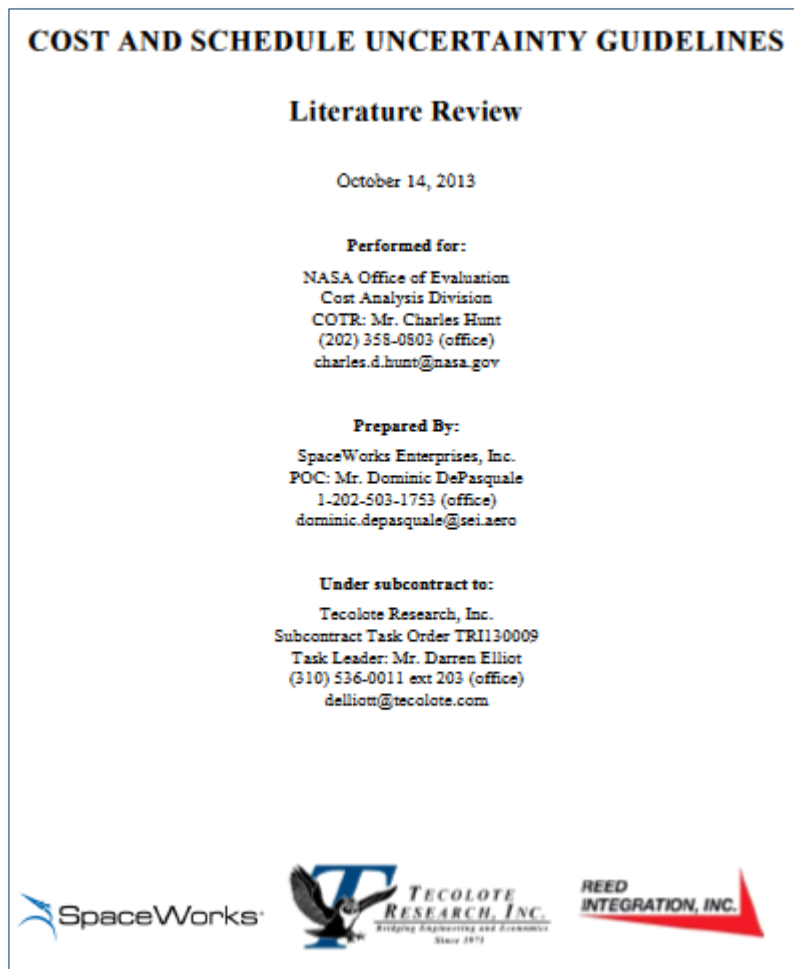Cost and Schedule Uncertainty Guidelines

Step 1 – Literary Research

Wide Range of Documents Researched

AACEI 17R-97	Christensen, P., et. al., "Cost Estimate Classification," AACE International Recommended Practice No. 17R-97, American Association for Cost Engineering International, November 2011.
AACEI 18R-97	Christensen, P., et. al., "Cost Estimate Classification: As Applied in Engineering, Procurement, and Construction for the Process Industries," AACE International Recommended Practice No. 18R-97, American Association for Cost Engineering International, February 2005.
AFCRUH, 2007	U.S. Air Force, U.S. Air Force Cost Risk and Uncertainty Handbook, 2007.
ASTM E2516-11	ASTM, "Standard Classification for Cost Estimate Classification System," Subcommittee E06.81 on Building Economics, ASTM International, 2011.
Baccarini, 1996	Baccarini, D., " The concept of project complexity - a review," International Journal of Project Management Vol. 14, No. 4, pp. 201-204, 1996.
Bearden, 2000	Bearden, David A., "A Complexity-based Risk Assessment of Low-Cost Planetary Missions: When is a Mission Too Fast and Too Cheap?", Fourth IAA International Conference on Low-Cost Planetary Missions, JHU/APL, Laurel, MD, May 2000.
Book, 2002	Book, S., "Schedule Risk Analysis: Why It is Important and How to Do It," presented at the Ground System Architectures Workshop (GSAW), The Aerospace Corporation, El Segundo, CA, March 2002.
Butts, 2013	Butts, G., "Uncertainty Approach," NASA Cost Symposium 2013, August 2013.
Cleden, 2009	Cleden, D., "Managing Project Uncertainty," Gower Publishing Company, 2009.
Cretu, 2009	Cretu, O., Berends, T., Stewart, R., "Reflections about Base Cost Uncertainty," Society for Risk Analysis Annual Meeting 2009, Risk Analysis: The Evolution of Science, Baltimore, MD, December 2009.
CSRUH, 2013	Naval Center for Cost Analysis, "Joint Cost Risk Uncertainty Handbook," 2013.
DOE, 2011	U.S. Department of Energy, "Cost Estimating Guide," DOE G 413.3-21, May 2011.
EPA, 2000	U.S. Environmental Protection Agency, "A Guide to Developing and Documenting Cost Estimates During the Feasibility Study," EPA 540-R-00-002, July 2000.
FAA Biz, 2013	U.S. Federal Aviation Administration, "Business Case Analysis Guidance," Office of Investment Planning and Analysis (AFI-1), July 2013.
FAA Cost, 2013	U.S. Federal Aviation Administration, "Business Case Cost Estimating Guide," Office of Investment Planning and Analysis (AFI-1), July 2013.
Filippazzo, 2004	Filippazzo, G., "Complexity Based Cost Estimating Relationships for Space Systems," IEEE Aerospace Conference, 2004.
GAO, 2009	Government Accountability Office, "GAO Cost Estimating and Assessment Guide: Best Practices for Developing and Managing Capital Program Costs," GAO Report GAO-09-3SP, 2009. GAO Cost Estimating and Assessment Guide
Garvey, 2006	Garvey, P., "Introduction to Systems Cost Uncertainty Analysis," MITRE Paper MP 05B0000012, presented at the National Institute of Aerospace Distinguished Lecture Series, May 2005.
Granli, 2009	Granli, O., "Project Uncertainty Management," MIT Open Courseware, Spring 2009.
Hulett, 2009	Hulett, D., "Integrated Cost-Schedule Risk Analysis using Risk Drivers and Prioritizing Risks," NASA Cost Symposium 2009.
LaserLight	Wonica, D., "Estimating Cost Uncertainty when only Baseline Cost is Available," LaserLight Networks, Inc., unknown publication date.
Leach, 2005	Leach, P., "Modeling Uncertainty in Project Scheduling," Proceedings of the 2005 Crystal Ball User Conference, 2005.
Leising, 2011	Leising, C., "Concept Maturity Levels," NASA PPMB, April 2011.
Little, 2006	Little, T., "Schedule Estimation and Uncertainty Surrounding the Cone of Uncertainty," IEEE Software, Published by IEEE Computer Society, May/June 2006.
McConnell, 1996	McConnell, S., "Rapid Development: Taming Wild Software Schedules" Microsoft Press, 1996.
MDA, 2012	U.S. Missile Defense Agency, "Cost Estimating and Analysis Handbook," MDA Director for Operations Cost Estimating and Analysis Directorate, June 2012.
NASA CEH, 2008	National Aeronautics and Space Administration (NASA), "NASA Cost Estimating Handbook," 2008.
Neatrour,2009	Neatrour, J. et al., "Fat-Tailed Distributions for Cost and Schedule Risk Analysis," presented at the NASA Cost Symposium, Kennedy Space Center, Florida, May 2009.
Nair, 2013	Nair, P., "Advocate Joint Confidence Level (JCL) Combined Resources Forum," June 2013.
Peterson, 2008	Peterson, C., et. al, "Rapid Cost Assessment of Space Mission Concepts through Application of Complexity-Based Cost Indices," IEEE Aerospace Conference, March 2008.
RAND, 2008	Fox, B., et. al., "Guidelines and Metrics for Assessing Space System Cost Estimates," RAND Technical Report, prepared for the U.S. Air Force, 2008.
Raymond, 1999	Raymond, F., "Quantify Risk to Manage Cost and Schedule," Acquisition Review Quarterly, Spring 1999.
Smart, 2011	Smart, C., "Covered With Oil: Incorporating Realism in Cost Risk Analysis, presented at the Joint Annual ISPA/SCEA Conference, Albuquerque, June, 2011.

Research Findings

COST AND SCHEDULE UNCERTAINTY GUIDELINES

Literature Review

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1. Data driven metrics derived based on percentage growth from a specific reference point – typically award

2. Metrics developed at a commodity or specific hardware level (e.g., subsystem)

3. Metrics categorized by level of technical challenge/complexity

4. Ranges decrease as technical understanding (design maturity) increases

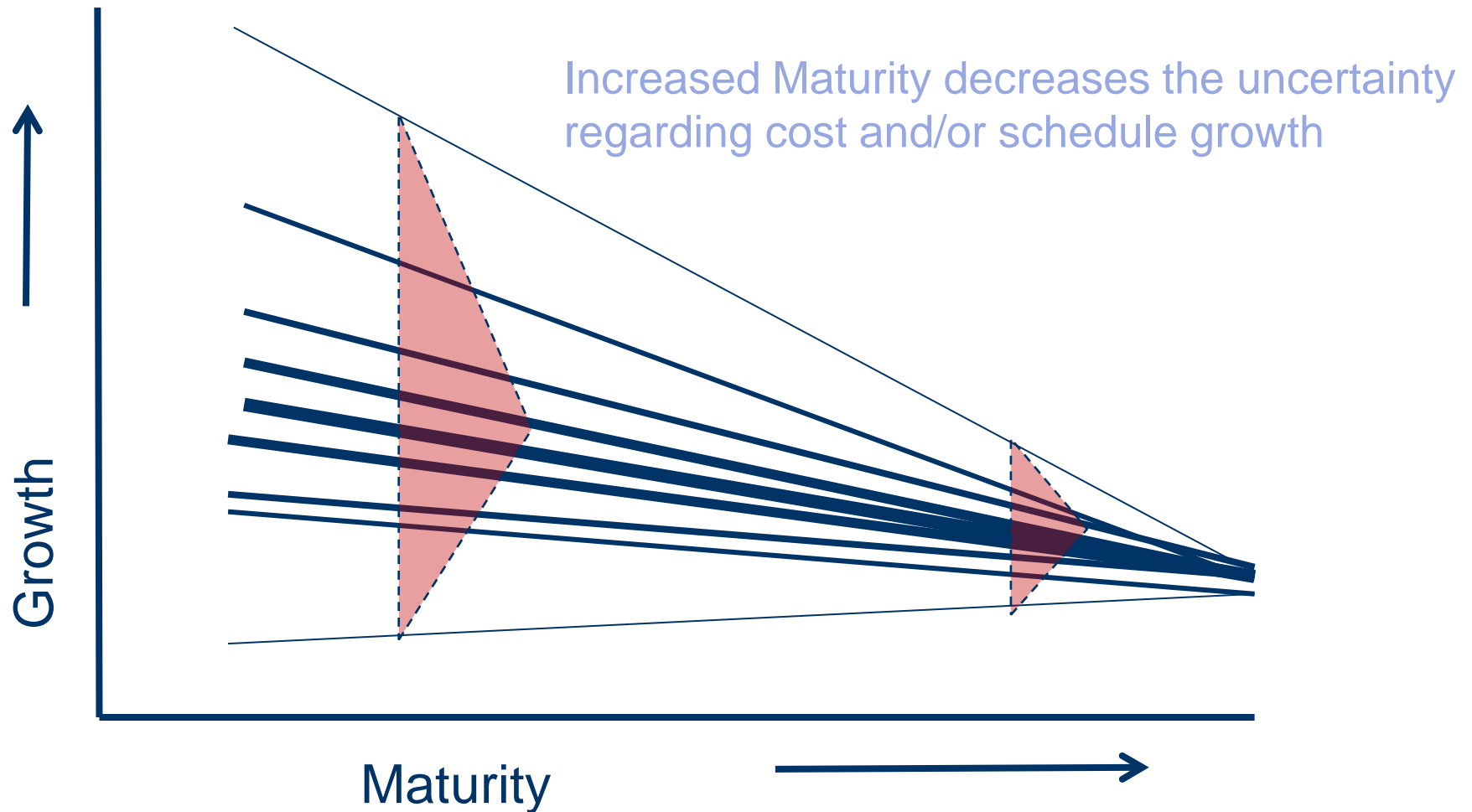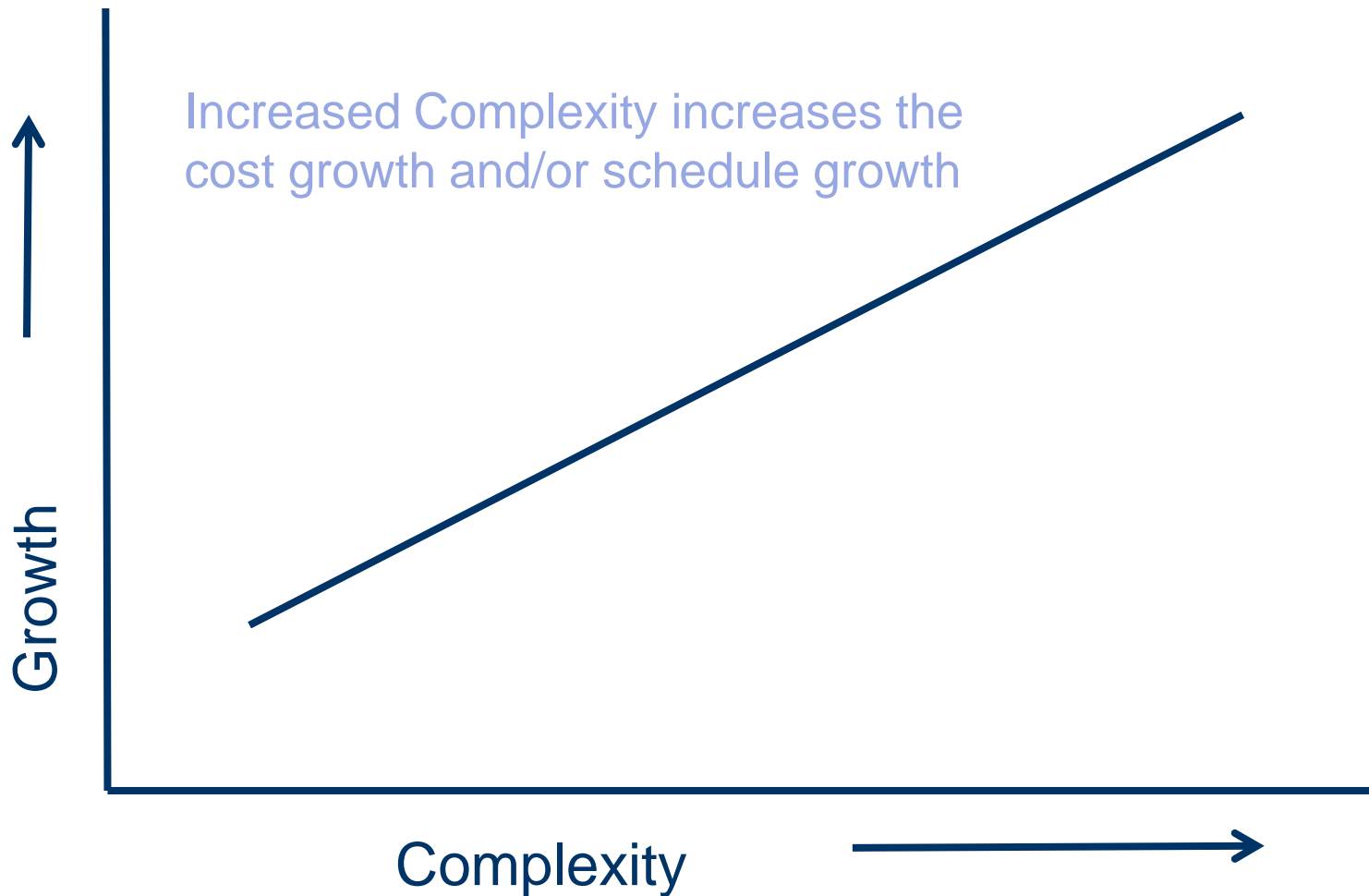5. No current tables are directly applicable to NASA PDR /CDR JCL's

Cost and Schedule Uncertainty Guidelines
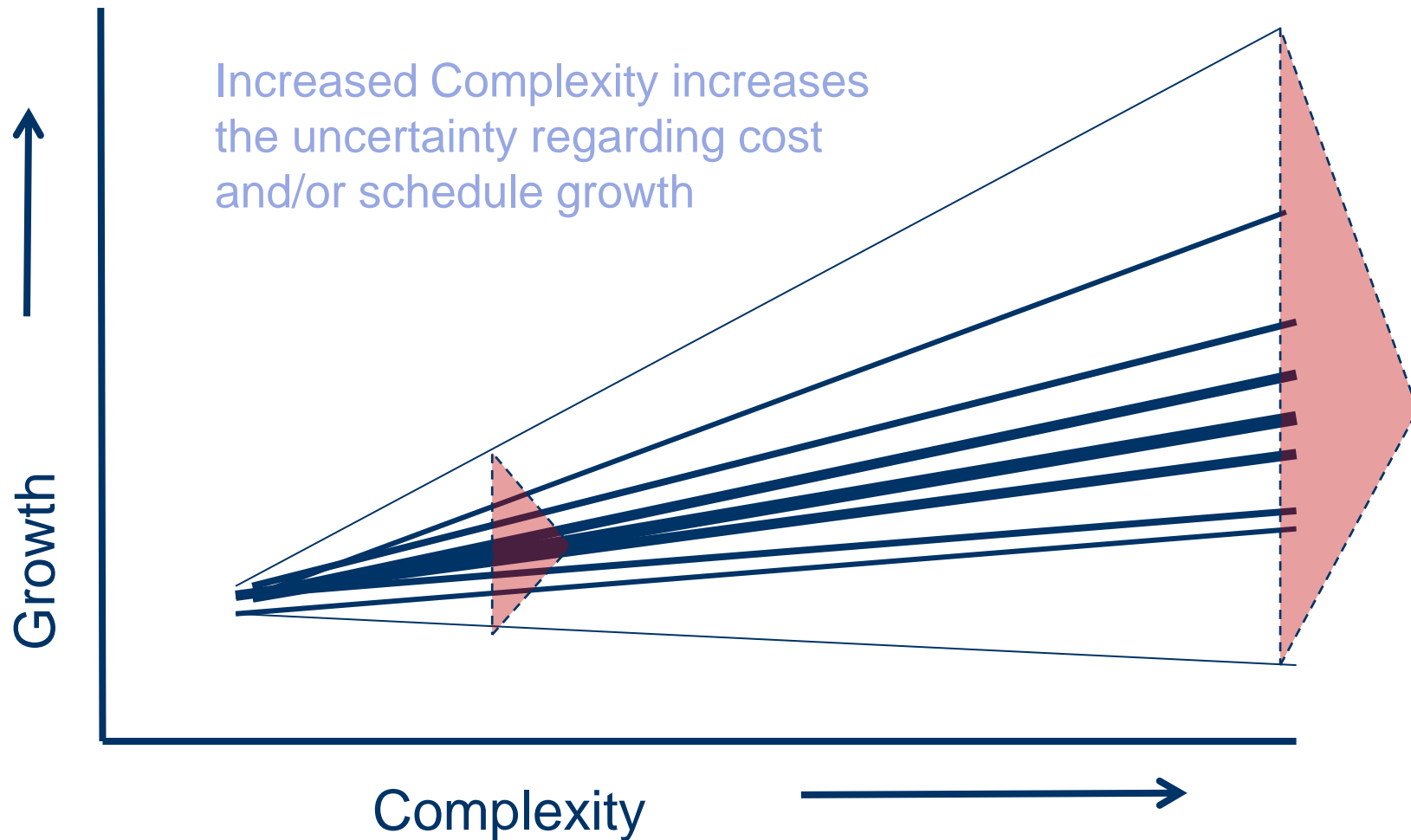
Step 2 – Framework Concept

Premise 1 – Uncertainty Decreases with Maturity

Increased Maturity decreases the uncertainty regarding cost and/or schedule growth

Growth

Maturity

Premise 2 – Increased Complexity has Higher Growth

Increased Complexity increases the cost growth and/or schedule growth

Growth

Complexity

Premise 3 – Increased Complexity has Higher Uncertainty

Increased Complexity increases the uncertainty regarding cost and/or schedule growth

Growth

Complexity

Guideline Tables

- Developed at specific hardware or work areas, based on data availability

- Meant as a reference point (anchor) for which project specific distributions can be generated

- Flexible to allow updates and expansion with additional data and/or research

		Technical Complexity		
		Low	**Medium**	**High**
Design Maturity	**CSR/SRR**	mean - X_{11} * Estimate std deviation - Y_{11} * Estimate	mean - X_{11} * Estimate std deviation - Y_{11} * Estimate	mean - X_{11} * Estimate std deviation - Y_{11} * Estimate
	PDR	mean - X_{21} * Estimate std deviation - Y_{21} * Estimate	mean - X_{21} * Estimate std deviation - Y_{21} * Estimate	mean - X_{21} * Estimate std deviation - Y_{21} * Estimate
	CDR	mean - X_{31} * Estimate std deviation - Y_{31} * Estimate	mean - X_{31} * Estimate std deviation - Y_{31} * Estimate	mean - X_{31} * Estimate std deviation - Y_{31} * Estimate

- *Maturity aligns with CADRe capture point*

- *Challenge is in defining "complexity"*

Background: RAND Report

Table 2.5
Thermal Cost Drivers

Cost Driver	Rating ↑ Cost Up ↓ Cost Down
Vehicle classification (Class A, B, C, or D)	
Class A space vehicle	↑↑↑
Class B space vehicle	↑↑
Class C space vehicle	↓
Class D space vehicle	↓↓
Long mission life	↑↑
Payload accommodation requirements	
Coupled payload instruments	↑↑
Isolated payloads/instruments	↓
Cryogenic application	↑↑
Orbital environment	
LEO	↓
MEO	↑
GEO	↑↑↑
MIL-STD-1540E thermal margins	
No tailoring of 11°C margin	↑↑
Reducing 11°C margin to 5°C	↓
Use of 2 phase heat pipes	
Use of capillary pumped loops	↑↑↑↑
Use of loop heat pipes	↑↑↑↑
Use of variable conductance heat pipes	↑↑
Use of constant conductance heat pipes	↑
No heat pipes	↓
Use of deployable radiators	↑↑
Development thermal vacuum testing	↑

SOURCE: AFCAA (2004).

- Report was created as a reference document for reviewing and assessing reasonableness of Air Force space vehicle cost estimates

- Draws heavily from AFCAA Training Curriculum (Spectrum Astro), "Space Vehicle Design" (Griffin & French) and SMAD (Wertz & Larson)

- Subsystem-by-subsystem technical considerations, cost estimating issues, and cost driver information may be indicators of complexity

Source: Fox, B., et. al., "Guidelines and Metrics for Assessing Space System Cost Estimates," RAND Technical Report, prepared for the U.S. Air Force, 2008
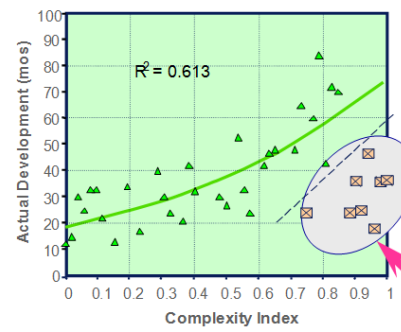
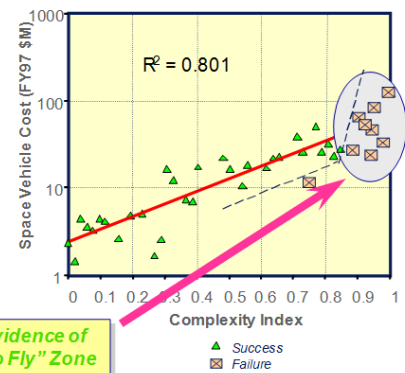SpaceWorks® — LIMITED RELEASE — 5

Background: CoBRA Method Results

Schedule as Function of Complexity — $R^2 = 0.613$

SV Cost as Function of Complexity — $R^2 = 0.801$

Evidence of "No Fly" Zone

▲ Success
▢ Failure

- Aerospace Corp. CoBRA method (circa 2000, 2004, 2008) demonstrated ability to relate cost and schedule to "complexity" for small spacecraft missions
- Modified versions of CoBRA have been implemented with mixed success by JPL and others

Source: Bearden, David A., NASA IPAO presentation, 2004.

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Aerospace CoBRA methodology and RAND study identified relationship between cost and technical complexity

- Ability to include both discrete and continuous attributes
- Fairly intuitive process with results traceable to inputs
- Successfully demonstrated for small spacecraft and other spacecraft applications
- RAND study indicated potential subsystem drivers
- CoBRA is a system level model

Pursued path to develop subsystem complexity model

- Derivative of Aerospace Corporation CoBRA methodology
- Approach and attribute selection informed by literature review, SEI SME, Tecolote data findings, and feedback from peer reviews (December 2013, March 2014)
- Complexity scoring at the subsystem level
- Complexity index results based only on attributes available from CADRe's

Source: Bearden, David A., "A Complexity-based Risk Assessment of Low-Cost Planetary Missions: When is a Mission Too Fast and Too Cheap?", Fourth IAA International Conference on Low-Cost Planetary Missions, JHU/APL, Laurel, MD, May 2000.

Complexity Index Calculation

Subsystem (WBS Element)

Attributes (Prog. / Technical)		Attribute Values		Complexity Score Calculation		Cmplx Index
Discrete Attribute	→	Up to 9 Options	→	-100% to +100%	→ Scaled according to significance →	Normalized Avg of Cmplx Score for all attributes
Continuous Attribute	→	Numerical Value	→	Percent Rank	→	

Subsystem 2 through n

System level*
- Spacecraft heritage
- Risk/reliability classification
- Mission life
- Number of organizations Involved
- Foreign partnership
- Number of major spacecraft separations
- Orbit/destination

Structures and Mechanisms
- Subsystem heritage
- Type of materials
- Subsystem modularity
- Number of deployments

Thermal Control Subsystem
- Risk/reliability classification
- Type of thermal control
- Mission life
- Nature of payload accommodations
- Orbit/destination

Guidance Navigation and Control
- Pointing accuracy

Electrical Power and Distribution
- Solar cell type (if applicable)
- Solar array configuration (if applicable)
- Battery type (if applicable)
- Battery capacity (if applicable)

Propulsion
- Subsystem heritage
- Propulsion type(s) on spacecraft
- Number of thrusters + tanks
- Thrust generated from all propulsion systems
- Spacecraft land/sample/return

Communication
- Downlink communication band
- Maximum downlink data rate
- Uplink communication band
- Maximum uplink data rate

Command and Data Handling
- Subsystem heritage
- Processor architecture
- Radiation hardening
- Data storage available

Payload
- Number of unique instruments
- Total mass
- Average complexity of instruments
- Payload average power

Instruments
- Mass
- Power
- Instrument type
- Starting TRL level
- Heritage

Integration and Test
- Spacecraft heritage

Spacevehicle

1 – Messenger
2 – STEREO
3 – AIM
4 – IBEX
5 – LRO
6 – CloudSat
7 – DAWN
8 – GRAIL
9 – JUNO
10 – Kepler
11 – OCO
12 – OSTM
13 – Phoenix
14 – Spitzer
15 – Calipso
16 – MRO
17 – GLAST
18 – AQUA
19 – COBE
20 – CONTOUR
21 – Deep Impact
22 – FAST
23 – GALEX
24 – GENESIS
25 – LANDSAT 7
26 – LCROSS
27 – Mars Pathfinder
28 – NEAR
29 – New Horizons
30 – RHESSI
31 – SAMPEX
32 – Stardust
33 – SWAS
34 – TIMED
35 – TRACE
36 – TRMM
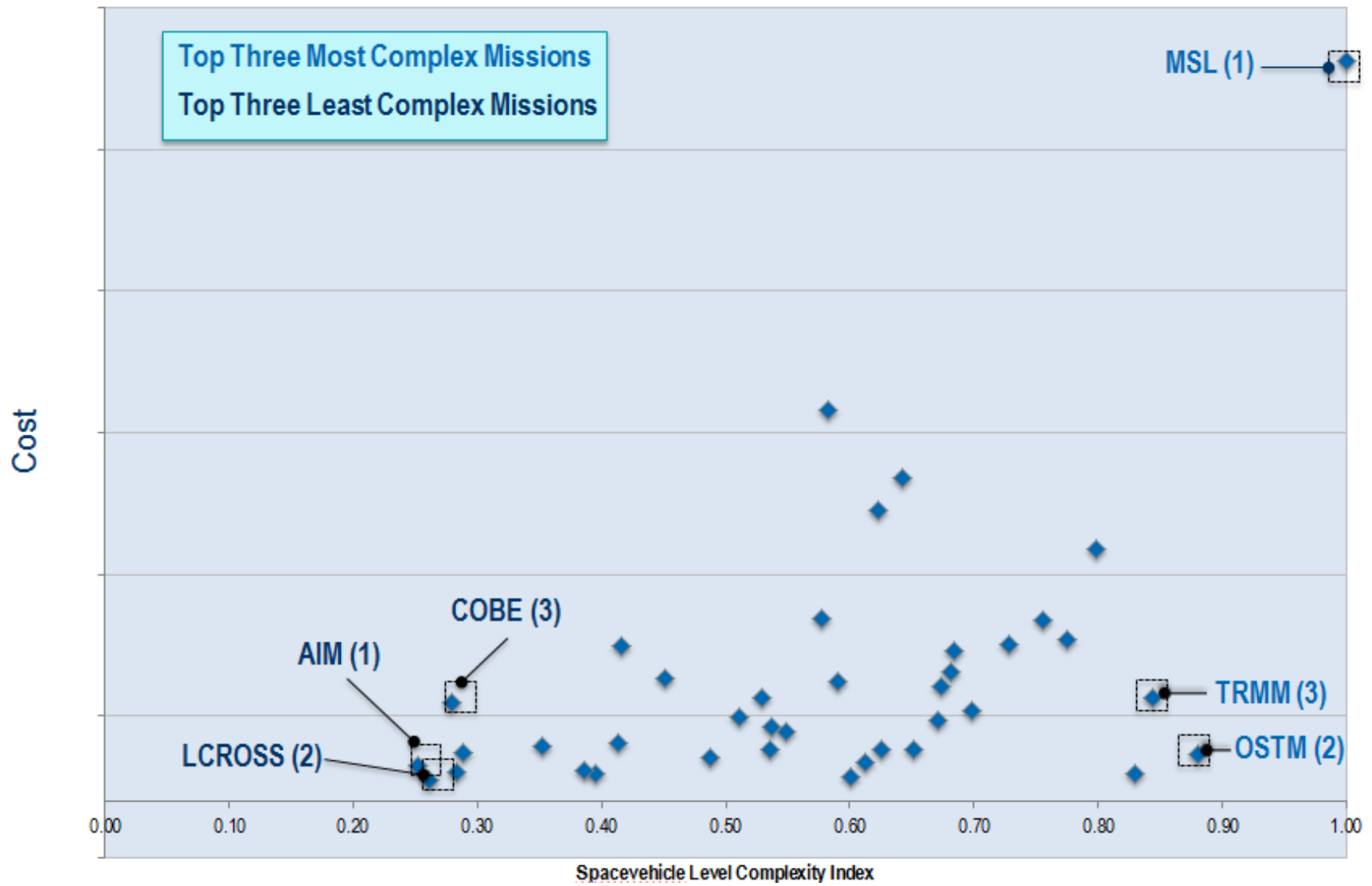37 – WIRE
38 – MSL
39 – MER
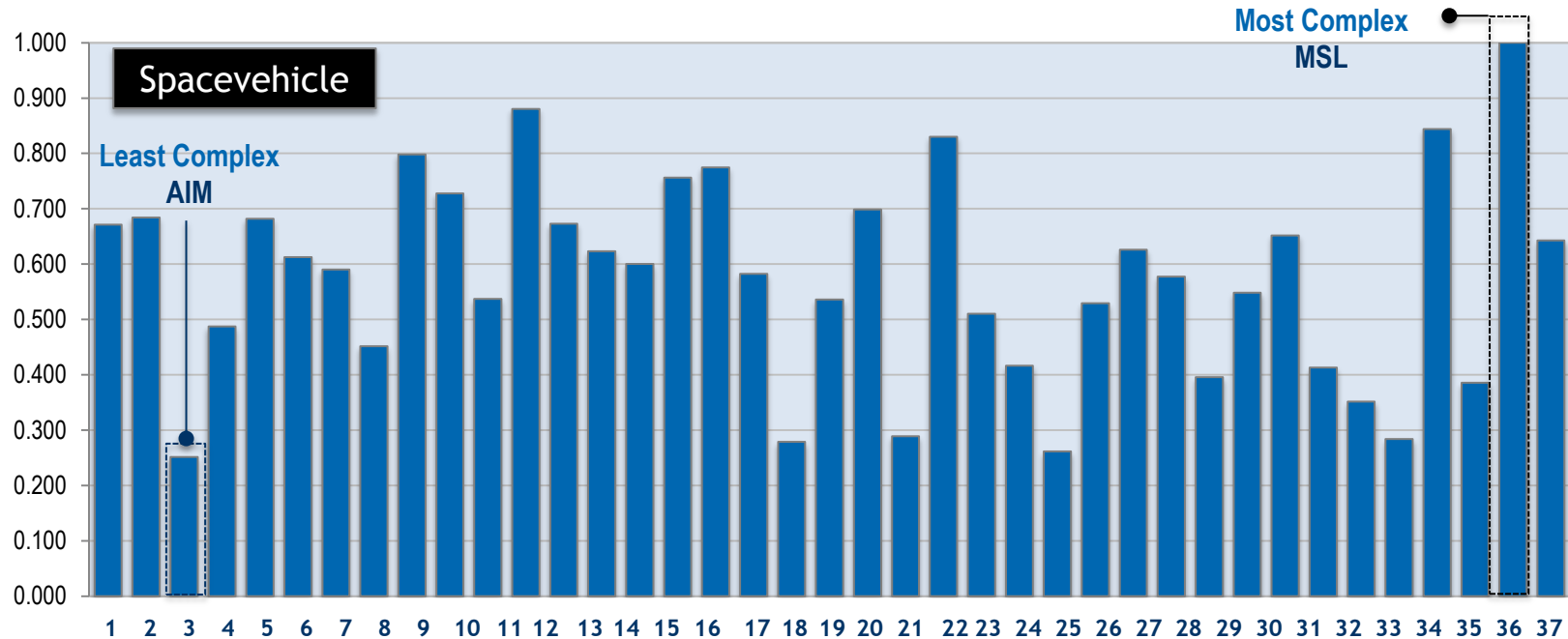
Five (5) Most Complex

- MSL (#36)
- OSTM (#12)
- TRMM (#36)
- GALEX (#23)
- JUNO (#9)

Five (5) Least Complex

- AIM (#3)
- LCROSS (#26)
- COBE (#19)
- TRACE (#35)
- FAST(#22)

Relationship Between Cost and Complexity

Challenges in the Framework

- Attributes limited to data available in CADRe, peer review identified additional potential drivers for consideration

- Some missions lacked all data, so removed from analysis – result is dataset reduced to 37 missions

- Calculations currently based on equi-weighting of attributes, some may need to have a higher weight

- Work in progress – but initial results indicate stratification potential or use to assess uncertainty vs complexity

Cost and Schedule Uncertainty Guidelines

Step 3 – Data Collection

Developed Mapped and Normalized Cost Dataset

- Identified 18 missions having a complete temporal (PDR, CDR, and launch) CADRe dataset

- Mapped time phased data to NASA standard subsystem WBS

- Normalized cost to BY2010$K

- Separated the cost into Phase A, Phase B/C/D, and Phase E

- Developed estimate growth factors for each WBS by milestone for Phase B/C/D
  - Launch Final Cost / CDR Estimate = CDR Growth Factor
  - Launch Final Cost / PDR Estimate = PDR Growth Factor

Developed a Normalized Schedule Dataset

- Developed standardized Schedule Collection structure

- Obtained source CADRe schedules for the 18 missions for which temporal cost data was available

- Captured key schedule dates from the source files

- Created 108+ work-day duration metrics by subsystem for 17 of the 18 missions

- Developed duration growth factors for the 108+ metrics

- Dataset enables:
  - Historical duration growth analysis for major work efforts
  - Alignment of cost and schedule metrics for correlation and sensitivity analysis
  - A framework for continued data collection
  - A potential template for a high-level schedule model for us in Phase A or parametric analysis

	Award	PDR	CDR	Obs I&T Start	PSR	Ship	Launch
Space Vehicle							

	Award	PDR	CDR	Subsystem Delivery	S/C I&T Start	S/C Delivery
Spacecraft						
Structures						
Thermal Control						
EPS						
GN&C						
Propulsion						
Communications						
C&DH						
Software						

	Award	CDR	Delivery
Instrument 1			
Instrument 2			
Instrument 3			
....			
Instrument n			

Challenges in Data Collection

- At time of the study, CADRe/ONCE contains raw project data (no normalized dataset) - extensive mapping, allocation, and normalization was required

- Although an extensive amount of missions in CADRe, only a subset (18) had multiple milestones captured

- Detailed schedule data is lacking in CADRe and source documents, additional focus needed to enhance capability to develop appropriate growth metrics

- Although limitations, the resulting dataset was consistent, complete, and useful for growth analysis – continued population of CADRe's will improve dataset and analysis

Step 4 – Analysis and Stratification

Does Growth Relate to Complexity?

CostGrowth Vs. Complexity
Correlation Coefficient = 0.0402
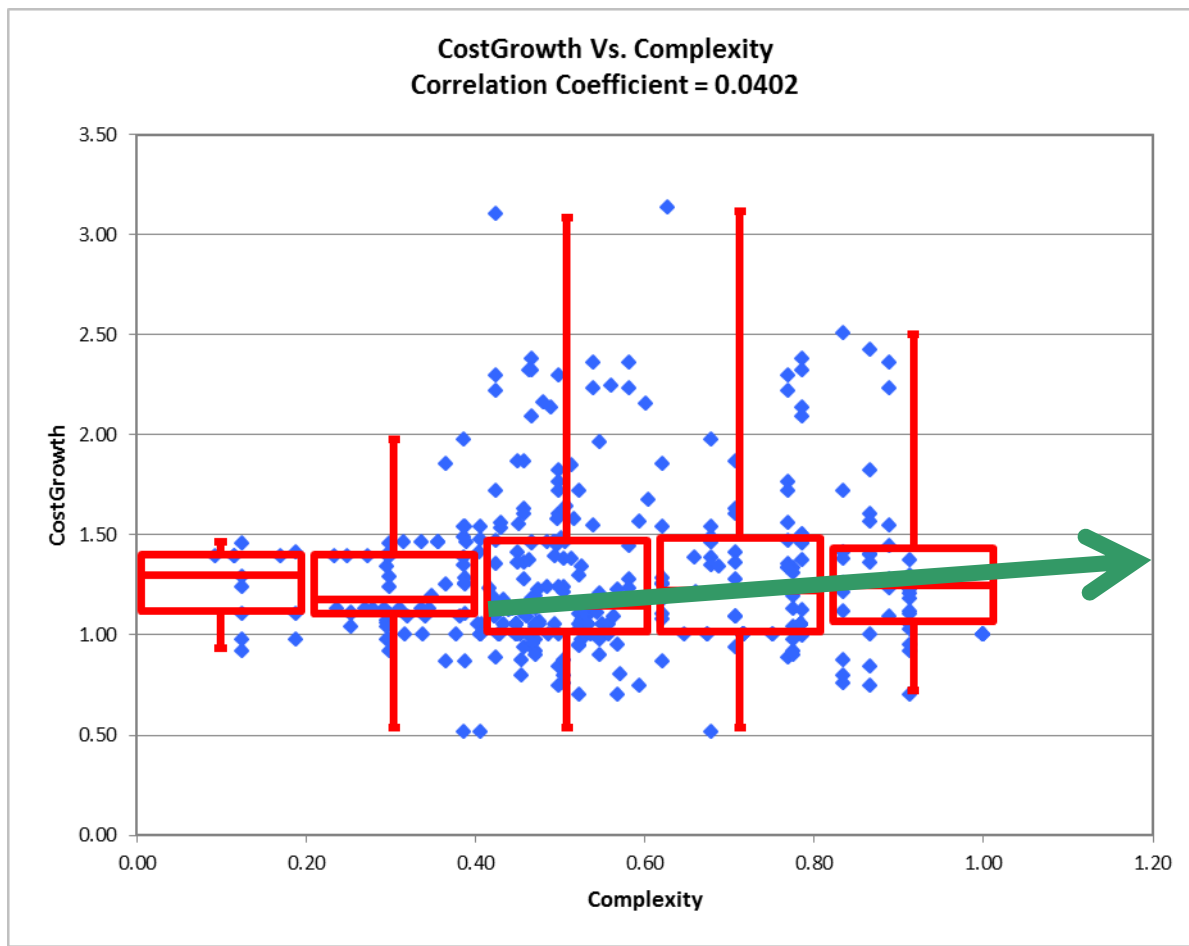
Used Three (3) Complexity Bins (Low, Med, High)
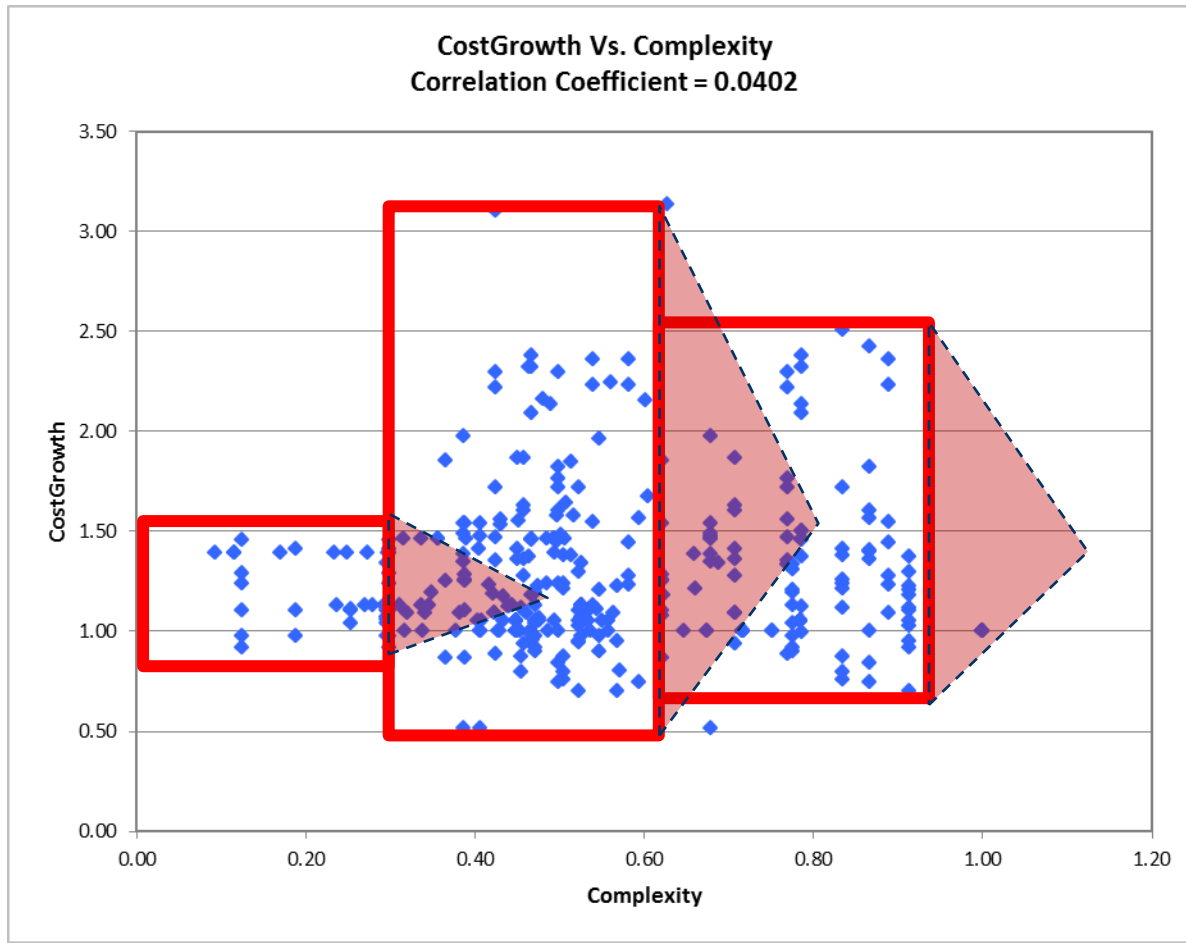
PDR Dispersion Slightly Higher than CDR
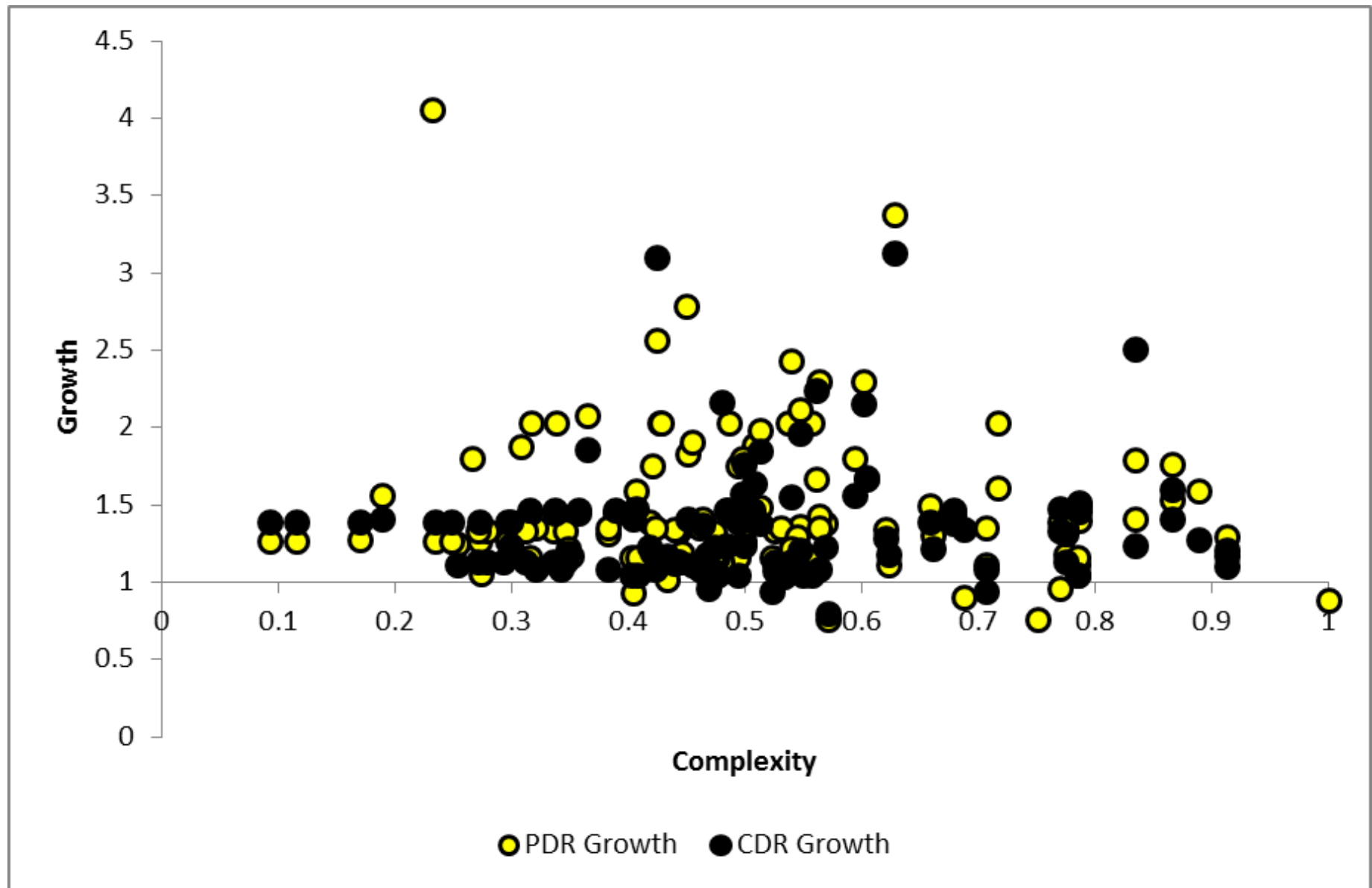
Distributions Determined from Bins
(Low = 0-0.4, Med = 0.4-0.7, High >0.7)

PDR	Low Complexity	Medium Complexity	High Complexity
Mean	1.409	1.521	1.353
Std Dev	0.254	0.459	0.312
CV	0.18	0.30	0.23

CDR	Low Complexity	Medium Complexity	High Complexity
Mean	1.303	1.372	1.335
Std Dev	0.184	0.435	0.355
CV	0.14	0.32	0.27
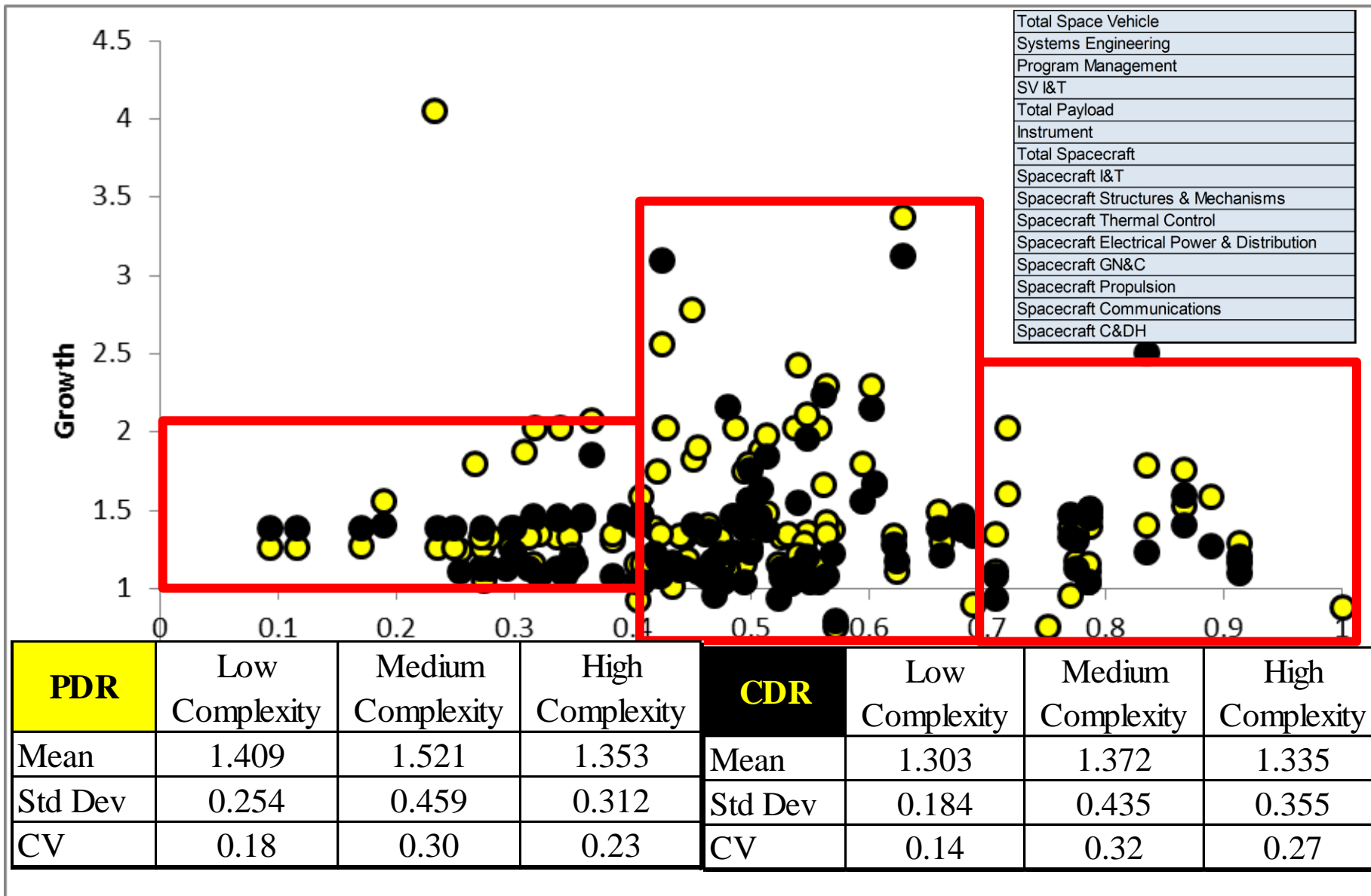
Duration Growth – All Subsystems

Legend:
- Space Vehicle PDR - Launch
- Space Vehicle SVI&T- Ship
- Spaceraft PDR - S/C I&T Start
- S/C I&T Start - S/C Dlvry
- Structures & Mechanisms PDR - SS Dlvry
- Thermal Control PDR - SS Dlvry
- EPS PDR - SS Dlvry
- GN&C PDR - SS Dlvry
- Propulsion PDR - SS Dlvry
- Communciations PDR - SS Dlvry
- C&DH - SS Dlvry
- Instrument PDR - Instrument Dlvry

PDR	Low Complexity	Medium Complexity	High Complexity
Mean	1.250	1.578	1.351
Std Dev	0.564	1.589	0.628
CV	0.45	1.01	0.46

CDR	Low Complexity	Medium Complexity	High Complexity
Mean	1.139	1.213	1.204
Std Dev	0.636	0.672	0.531
CV	0.56	0.55	0.44

Challenges in Data Analysis

- Sample size of 18 missions is small - aggregation of all data points allows for investigation of premise (complexity affects growth range) and to ascertain bins
  - Due to small sample size, some bins for subsystems are non-existent or have very limited data points (1-3)
  - Low complexity bins for some subsystems showed a higher growth and dispersion than the Medium complexity – opposite of expectations

- Many metrics to report for duration, identified a subset for use and publication

- Cost distributions need to be developed for TI and TD (Burn Rate) aspects

- Distributions identified are typically at a level higher than JCL model inputs

- Duration distributions should ideally be at task level, available data is not at that granularity

Cost and Schedule Uncertainty Guidelines

Step 5 – Calibration

Four Areas of Calibration

Determining project specific relevant range

Distributions for TI and TD (Burn Rate)

Derivation of distributions for lower-level of detail

Mechanism for avoiding risk double-count

Historical Distributions are Starting Points

- **Growth distributions based on historical projects provide a reference point (starting position)**

- **Through understanding the projects in the dataset, analysts can adjust the distribution**

- **Identification of differences provides rationale for why the historical range is not relevant and enables determination of reasonable distribution for the project**

  - If the project is deemed to more mature - scale both the average growth and dispersion

  - If the project is deemed to be less complex - scale the average growth

  - If the project is deemed to have less risk/uncertainty - scale the dispersion

Reference Distribution

More Mature

Less Complex / Risky
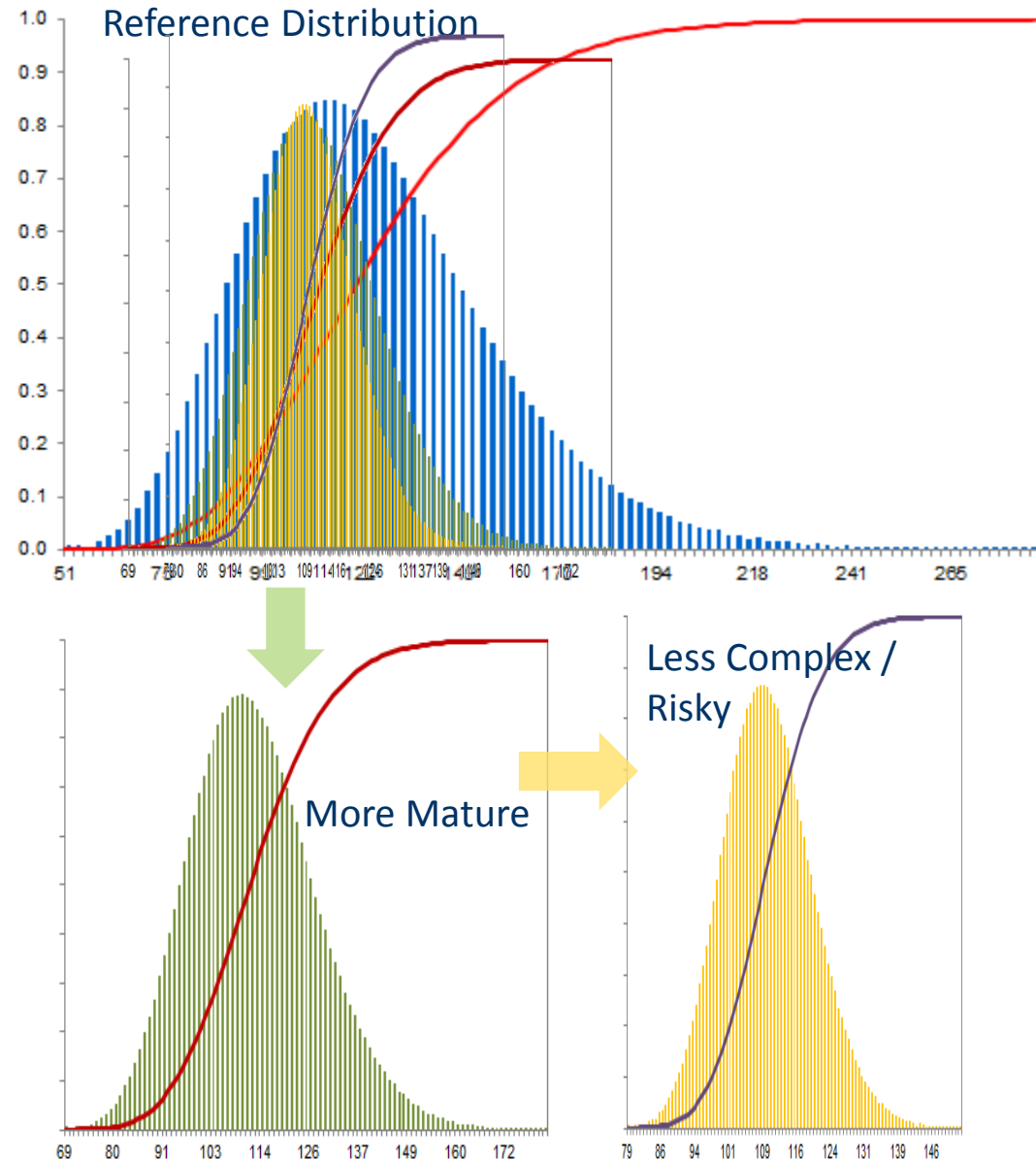
JCL models require TD and TI distributions

- **Total Time Dependent (TD) costs are affected by duration and burn rate**

- **Objective is to develop historical growth on burn rates**

  - Step 1: Determine TD portion of Total Cost
  - Step 2: Divide TD by relevant duration
  - Step 3: Analyze growth

- **Analyzed six (6) recent JCL models to identify average TD ratio by subsystem**

- **Used average TD ratio to break out subsystem cost by phase into TD and TI buckets**

Subsystem	TD %
Education & Public Outreach	90%
System Integration, Assembly, Test & Check Out	77%
Spacecraft I&T	24%
Spacecraft Software	98%
Spacecraft C&DH	45%
Spacecraft Communications	54%
Spacecraft Propulsion	58%
Spacecraft GN&C	57%
Spacecraft Electrical Power & Distribution	52%
Spacecraft Thermal Control	76%
Spacecraft Structures & Mechanisms Total	54%
Spacecraft Product Assurance	85%
Spacecraft Systems Engineering	99%
Spacecraft Management	59%
Flight System Product Assurance	85%
Flight System Systems Engineering	99%
Flight System Project Management	59%
Payload Integration, Assembly Test & Check out	77%
Instrument(s)	58%
Payload Product Assurance	85%
System Engineering	99%
Payload Management	70%
Science/Technology	93%
Safety and Mission Assurance	85%
Systems Engineering	93%
Project Management	96%

TD (Burn Rate) Cost Growth – All Subsystems
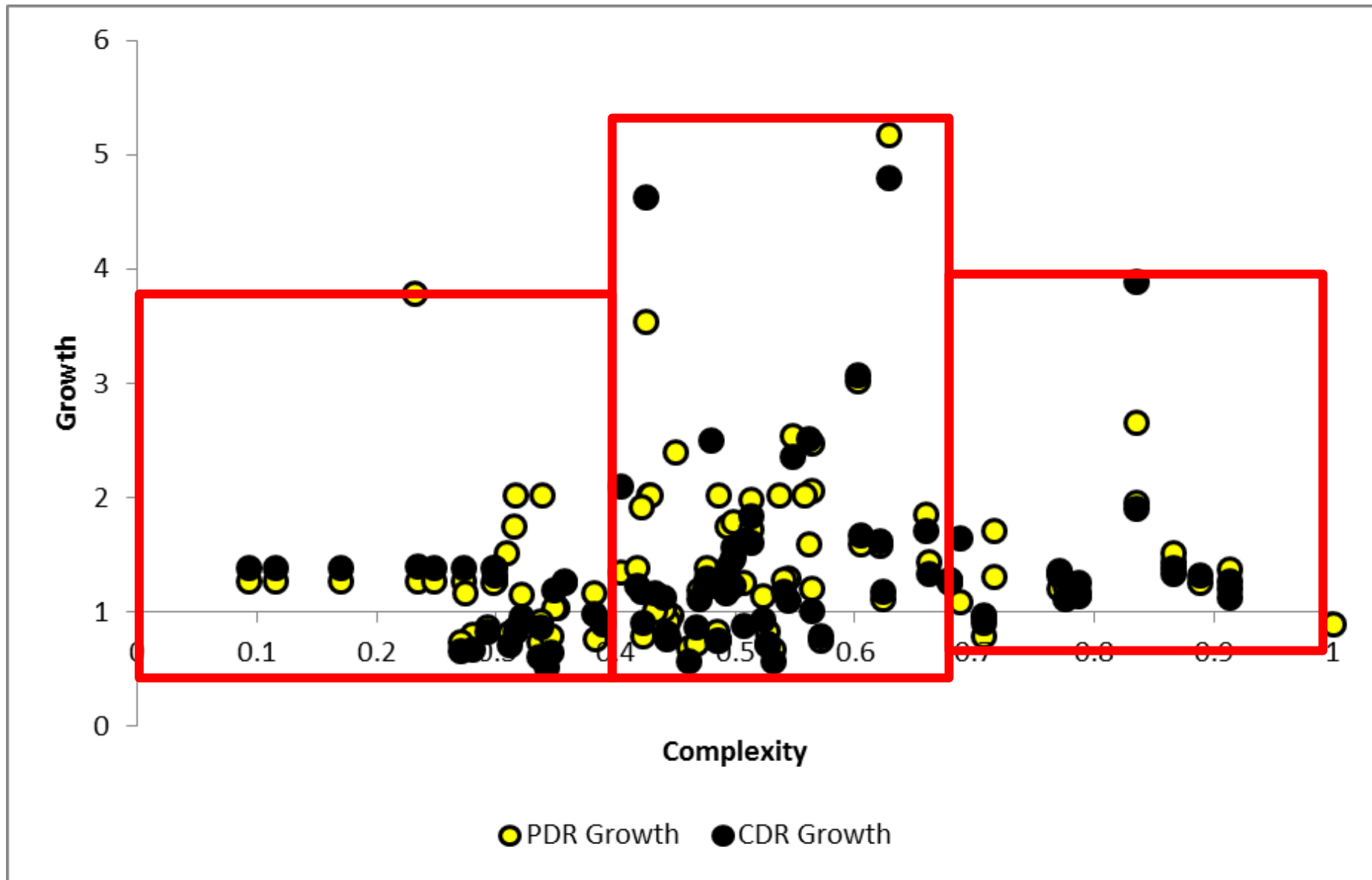
Time Independent (TI) Cost Growth (all subsystems)
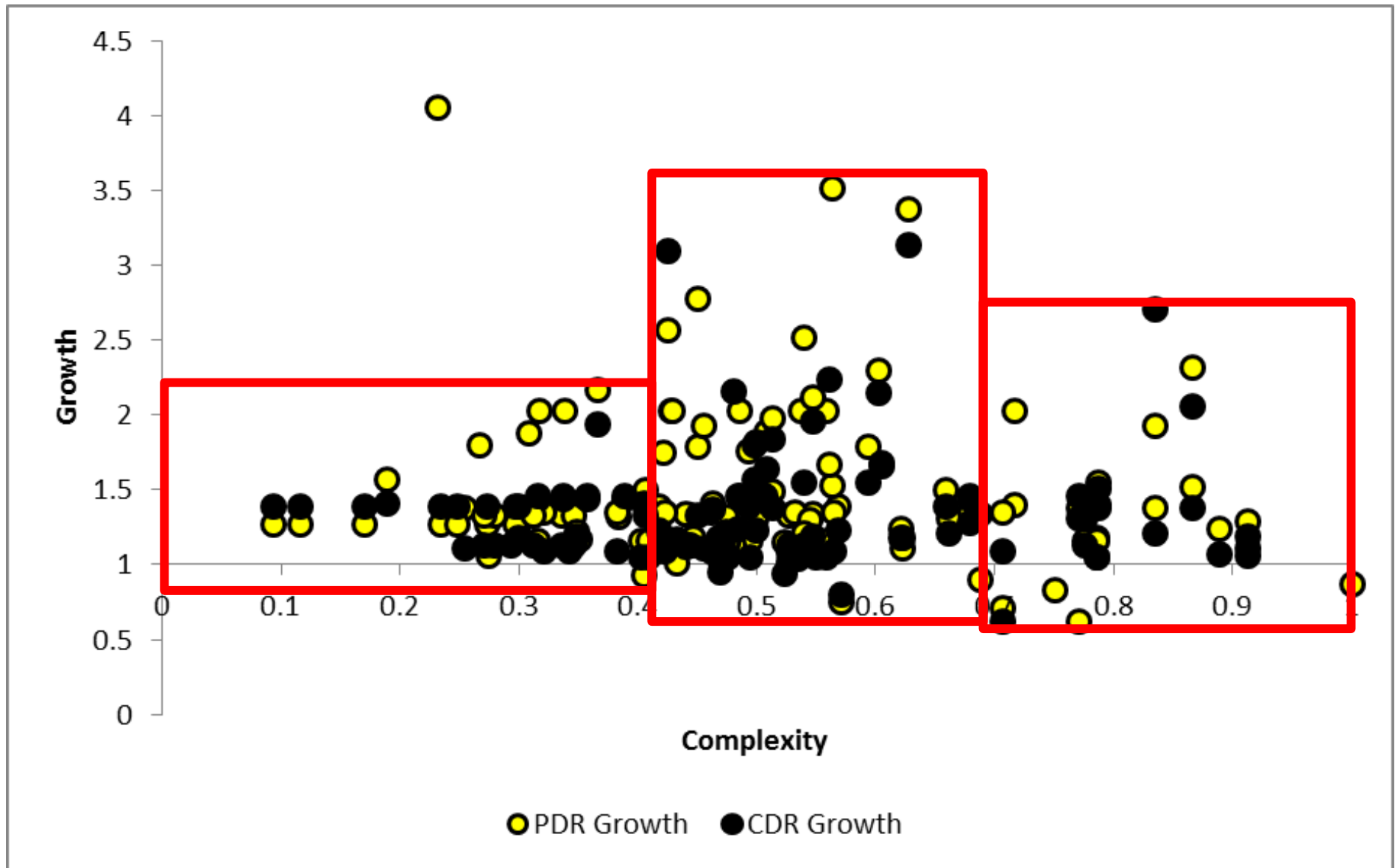
Considerations for Lower Level Application

- Schedule models differ from cost models – order versus summation statistics

- In summation models, analytic techniques can be used to derive summation distributions from lower level distributions.

- Conversely, given certain conditions, lower level distributions can be derived from a summary distribution. Note: lower level distributions will be broader than summary

- Reducing the network under a schedule summary to a linear path enables similar methods to apply
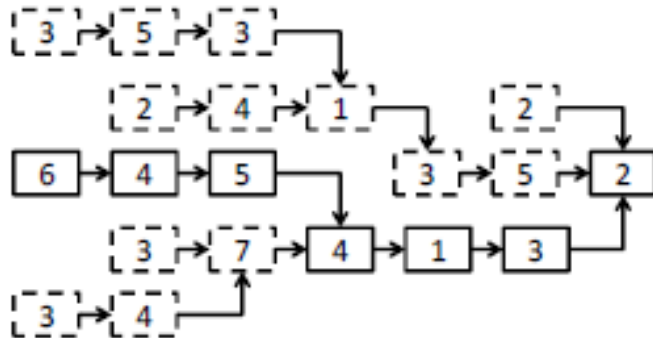
Analytic Method for Probabilistic Cost
and Schedule Risk Analysis

Final Report

5 April 2013

PREPARED FOR:

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Source: Book, S.A ,Schedule Risk Analysis: Why it is Important and How to Do It," GASW Workshop 2002, March 2002

The Equation – Solving for Lower Level Distributions to Match Summary Mean and 80% value

- **Basic Formula**

Given a WBS of n elements, $X_1, X_2,....,$ and X_n, the formula to compute the variance of the total is given by

$$\sigma^2_{Total} = \sum_{i=1}^{n} \sigma_i^2 + 2 \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \rho_{ij}\, \sigma_i \sigma_j = \boldsymbol{\sigma'} \sum \boldsymbol{\sigma} \tag{1}$$

where:

n is the number of WBS elements, which can be any positive integer
σ_{TOTAL} is the standard deviation of the total
σ_i is the standard deviation of the ith element, X_i (i = 1,...,n)
ρ_{ij} is the pairwise correlation between X_i and X_j (i, j = 1,...,n)
$\boldsymbol{\sigma'} = (\sigma_1, \sigma_2, ..., \sigma_n)$
$\sum$ = the correlation matrix of the WBS elements

- **Given an assumed correlation**

If the user specifies a global correlation coefficient for all WBS elements, we can also calculate the respective PEV measure to match the total variance. The formula to calculate the PEV is given below:

$$PEV = \left(\frac{\sigma^2_{Total}}{\sum_{i=1}^{n} p_i^2 + (\rho_G)\,\mathbf{P'(E-I)P}} \right)^{0.5} = \left(\frac{\sigma^2_{Total}}{\sum_{i=1}^{n} p_i^2 + 2(\rho_G)\sum_{i=1}^{n-1} \sum_{j=i+1}^{n} p_i p_j} \right)^{0.5} \tag{3}$$

where:

p_i is the point estimate of the ith element, X_i (i = 1,...,n)
$\mathbf{P'} = (p_1, p_2,....., p_n)$
ρ_G is the user-specified global pairwise correlation between X_i and X_j (i, j = 1,...,n)

Using the PEV from Equation 3 and the user-specified correlation coefficient, the standard deviation at the total level will match the target number.

Calculating the Resulting Log-Normal Distributions

Log-Normal Distribution. Since the distribution at the total level is most likely log-normal, we applied the log-normal distribution to approximate the individual WBS elements. Given the unit-space mean (Mean) and standard deviation (Stdev), its log-space mean (μ_L) and standard deviation (σ_L) are derived as follows:

$$\sigma_L = \sqrt{\ln\left(1 + (Stdev/Mean)^2\right)} = \sqrt{\ln\left(1 + CV^2\right)} \tag{4}$$

$$\mu_L = \ln(\text{Mean}) - (\sigma_L)^2/2 \tag{5}$$

Consequently, its 80th percentile is given by

$$80^{th} = \exp(\mu_L + \text{NormsInv}(0.8)*(\sigma_L)) = \text{LogInv}(0.8, \mu_L, \sigma_L) \tag{6}$$

We used Equations 4 and 5 to generate the log-normal distributions for the individual WBS elements and we used Equation 6 to estimate the 80th percentile for the total.

Summary Distribution Allocation Process
(Reducing to a Linear Path)

Task Name	Duration	Total Slack	Start	Finish
▲ **Summary**	**32 days**	**0 days**	**Mon 8/4/14**	**Tue 9**
Task 7	6 days	0 days	Mon 8/4/14	Mon :
Task 8	4 days	0 days	Tue 8/12/14	Fri 8/
Task 9	5 days	0 days	Mon 8/18/14	Fri 8/
Task 14	4 days	0 days	Mon 8/25/14	Thu 8
Task 15	1 day	0 days	Fri 8/29/14	Fri 8/
Task 16	3 days	0 days	Mon 9/1/14	Wed
Task 20	2 days	0 days	Thu 9/4/14	Fri 9/
Task 21	2 days	0 days	Mon 9/8/14	Tue 9
Task 23	3 days	0 days	Wed 9/10/14	Fri 9/
Task 24	2 days	0 days	Mon 9/15/14	Tue 9

3) Reduce to a Linear Path

Summary Distribution Allocation Process
(Calculating Lower Level Distributions)

Task 7	6.0
Task 8	4.0
Task 9	5.0
Task 14	4.0
Task 15	1.0
Task 16	3.0
Task 20	2.0
Task 21	2.0
Task 23	3.0
Task 24	2.0

1 – enter durations

PE	Mean Growth	Std Dev % (PEV = SD/PE)
32	25%	20%

2 – specify summary statistics

Given Correl:	0.60
Calc_PEV:	24.84%

3 – specify correlation and calculate PEV

	mean mxplr	PEV (StdDev%)
Task 7	125.00%	24.84%
Task 8	125.00%	24.84%
Task 9	125.00%	24.84%
Task 14	125.00%	24.84%
Task 15	125.00%	24.84%
Task 16	125.00%	24.84%
Task 20	125.00%	24.84%
Task 21	125.00%	24.84%
Task 23	125.00%	24.84%
Task 24	125.00%	24.84%

4 – determine distributions

Summary Distribution Allocation Process
(Implementing Distributions)

- **For tasks on the identified path, use the calculated distributions**

- **For tasks not on the path, use the summary distribution with the mean growth slightly lower**

- **Apply the correlation assumption**

Summary Distribution Allocation Process
(Verifying Result)

■ **Compare calculated distribution versus target for mean and 80%**

Multiple cases
Summary (Duration)
Calculated with 2000 iterations, CV (Point Estimate) = 0.160

Legend: Point Estimate (cdf) — Mean — 80% Probability Level — JACS Run

Cumulative Distribution Function	5%	10%	15%	20%	25%	30%	35%	40%	45%	50%	55%	60%	65%	70%	75%	80%	85%	90%	95%
Summary Distribution	30.411.	32.219.	33.496.	34.553.	35.483.	36.338.	37.149.	37.937.	38.715.	39.497.	40.295.	41.123.	41.993.	42.935.	43.966.	45.158.	46.570.	48.433.	51.298.
Allocated Distributions	30.778.	32.384.	33.758.	34.742.	35.615.	36.510.	37.413.	38.109.	38.808.	39.502.	40.371.	41.297.	42.144.	43.029.	44.135.	45.225.	46.501.	48.484.	50.992.

Avoiding Double-Counting for Risks
(Background)

- **Use of historical data, implies the capture of typical risks affecting past projects**

- **Best practice implies understanding the risks inherent in the dataset, and modeling only the additional risks**

- **Recent studies by NASA HQ has identified challenges in identifying the specific risk events that have occurred on historical projects**

- **Is there a middle road?**
  - Can projects include all identified risks to ensure the nuances of their occurrence ripples into their project plans?
  - Can the reference distribution be adjusted to account for a subset of risks that are deemed to be in the historical data?
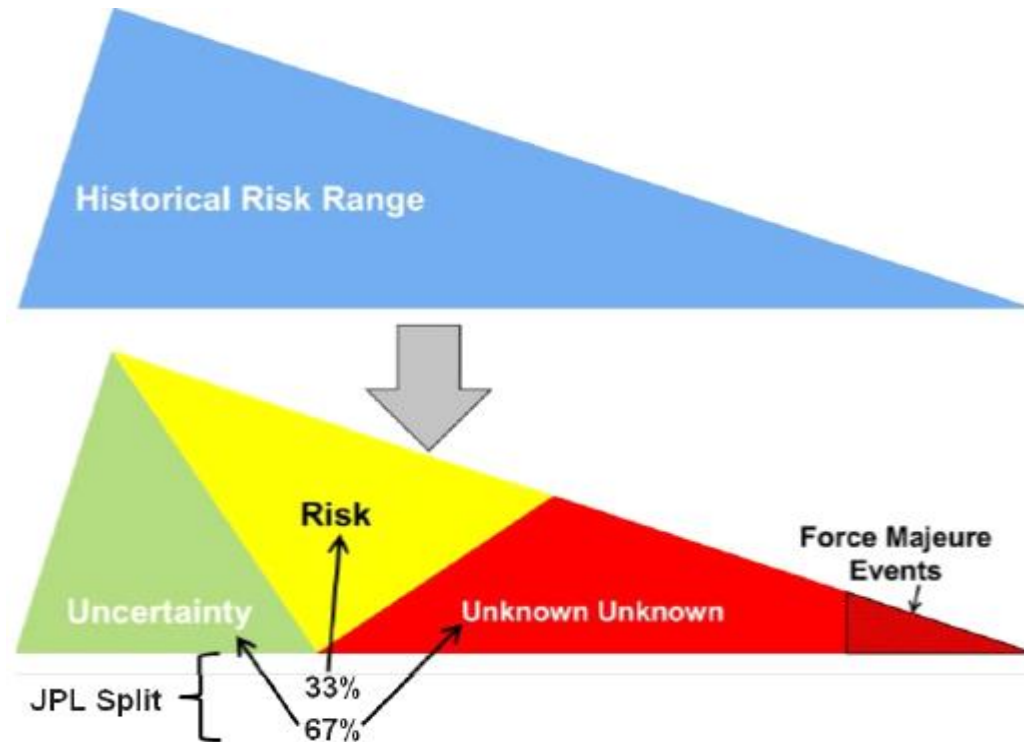
Source: Butts, Glenn, "Uncertainty Approach, " NASA Cost Symposium 2013, August 2013

Adjusting Reference Distribution
(Process)

Implement all risks into a JCL Model

Identify which risks are considered be included in the dataset (double-count risks)

Run the model with uncertainty off and only the double-count risks activated

Obtain cost and schedule statistics (point estimate, mean, standard deviation) for the appropriate summaries

Calculate an adjusted reference distribution by determining the distribution needed to combine with double-count risks to replicate the original reference

Avoiding Double-Counting for Risks
(Calculation)

- **Identify Reference Distribution, for example**
  - Estimate = 100
  - Mean growth = 30%; mean = 130
  - Std Dev = 25%; std Dev = 25

- **Calculate statistics for model with double-count risks and no uncertainty, for example**
  - Estimate = 100
  - Mean growth = 10%; mean = 110
  - Std Dev % of PE = 5%; std Dev = 5

- **Solve adjusted reference distribution**
  - Adjusted Mean = reference mean – mean of double-count risk
    - 130 – 110 = 120; 20% mean growth
  - Adjusted Std Dev % of PE (PEV) = Adj Std Dev / PE = ((reference SD ^2) – (double count SD^2)) ^(0.5)) / pt estimate
    - Adjusted Std Dev = $(((25^2)-(5^2))^{0.5})$;
    - $= ((625-25)^{0.5})$ 0;
    - $= (600^{0.5})/100$;
    - = 24.4949; PEV = 24.4949%

WBS/CES Description	Point Estimate	Mean	Std Dev	80%
Target Total (Reference Distribution)	$ 15,300.000 (12%)	**$19,889.85**	$3,824.82	**$23,189.04**
JCL Model	$ 15,300.000 (12%)	**$19,889.97**	$3,770.53	**$23,169.59**
Adjusted Reference	$ 15,300.000 (21%)	$18,431.93	$3,673.86	$21,592.15
Discrete Risks -Doublecount	$0.00	$1,458.05	$850.25	$2,255.89
Risk 1	$0.00	$162.22	$346.75	$858.84
Risk 2	$0.00	$16.73	$35.98	$82.33
Risk 3	$0.00	$3.62	$7.91	$15.81
Risk 4	$0.00	$5.05	$11.35	$19.42
Risk 5	$0.00	$101.36	$139.36	$258.20
Risk 6	$0.00	$48.50	$109.42	$190.33
Risk 7	$0.00	$341.23	$436.71	$900.55
Risk 8	$0.00	$16.77	$36.07	$82.78
Risk 9	$0.00	$3.55	$7.78	$15.37
Risk 10	$0.00	$5.04	$11.33	$19.94
Risk 11	$0.00	$168.23	$145.42	$314.17
Risk 12	$0.00	$161.99	$346.29	$855.97
Risk 13	$0.00	$4.73	$20.75	
Risk 14	$0.00	$1.01	$4.50	
Risk 15	$0.00	$5.17	$11.61	$20.19
Risk 16	$0.00	$161.73	$345.74	$855.02
Risk 17		$16.68	$35.88	$82.58
Risk 18	$0.00	$3.66	$8.00	$16.11
Risk 19	$0.00	$4.95	$11.11	$19.16
Risk 20	$0.00	$161.90	$346.07	$857.74
Risk 21	$0.00	$4.72	$20.73	
Risk 22	$0.00	$1.04	$4.62	
Risk 23	$0.00	$10.91	$14.83	$28.41
Risk 24	$0.00	$35.29	$45.54	$92.49
Risk 25	$0.00	$0.98	$4.38	
Risk 26	$0.00	$10.99	$14.98	$28.65

Challenges in Calibration

- Application in JCL models requires specification of TD and TI uncertainty distributions, improvement in data collection in CADRe's to provide visibility at subsystem will improve overall quality of results for these parameters

- Technique for allocating summary to details requires several major assumptions
  - The identified critical path is the major critical path for all simulation runs
  - All risks on the critical path have the same risk posture
  - Technique ignores impact from links external to the summary

- Obtaining data on actual task level variance grouped by duration length and effort phase (design, fabrication, test, etc) and WBS will provide enhanced duration metrics

- Removal of double-count risk requires indication of what risks historically affect projects, improvement in data collection to categorize and identify risk resolution on past projects will improve capability in the field.

Next Steps

In Conclusion…

Guidance
- NASA has enough information to make informed uncertainty decisions – the data is there!
- Definitive guidance will be difficult to produce for inputs
- Data does allow for general guidelines for cross-checks

Data
- Data collection has come along way in the last 10 years
- There are still many areas to improve upon
  - Activity level task duration actuals
  - Consistent CBS between projects
  - TD and TI breakouts
  - Correlation assumptions

Capability
- **Product is a work in process**
  - Additional work on all areas (complexity generation, data fidelity, data analysis/trends, etc)

Forward Plan
- **Data will be made available to community (ONCE) in September time frame**
- **There are other techniques* to tackle this problem that need to be incorporated in the uncertainty "portfolio"**

*Several examples are being presented at this Symposium!

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